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Cross-Layer Optimization for Wireless Systems: A European Research Key Challenge

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A new design paradigm has recently arisen in wireless communications research: so-called cross-layer optimization. In fact, this implies the redefinition of the overall design strategies for this kind of system as it breaks the classical open systems interconnection (OSI) model. The endless need for higher bit rates, stringent quality of service (QoS) requirements, and need for anytime anywhere wireless connections lead to the necessity of squeezing to the outmost the available radio bandwidth. Cross-layer plays a key role in achieving this goal. Literature on cross-layer-related issues is still relatively scarce, but recently published results show that the potential obtainable gains deserve the increasing attention cross-layer is getting. European research efforts on this topic have been increasing in the last years, and currently active research lines on this topic are gaining relevance.

New Design Concept

During the last decade, significant growth of digital wireless communications systems has arisen. Wireless networks initially inherited the traditional OSI-layer-based architecture from wired networks, where each layer is worked out based on its parameters as a separate entity. The OSI model is a widely known, well accepted framework for communication systems [1, 2]. With this model, systems are decomposed in seven layers (physical, link, network, transport, session, presentation, and application). Each is responsible for a subset of the system's operational functions. Messages are interchanged between entities of the same layer in both the transmitter and receiver. Each layer is aware of its own messages and embeds its information into upper layer messages when they go down in the layer stack, while it discards the lower layers' information when messages go up.

This model has proved to be quite useful for developing smart algorithms and techniques for different communication systems, achieving proper working mechanisms. However, advances attained in the different OSI layers have barely taken into account those achieved in other layers. Traditionally each layer's research has widely ignored the other layers. Even though this consideration simplifies protocol design and treatment, it seems to be suboptimal for wireless communication systems. This is due to the fact that the wireless medium is available to multiple users who intend to get access and transmit their information, and its inherent variability in both the time and frequency domains.

Although a variety of different layer schemes have been designed for wireless systems in order to efficiently manage

■ **Figure 1.** *Possible cross-layer communications.*

the scarce radio resources and provide certain QoS requirements to mobile users, the performance of such systems can be optimized by considering some vertical coupling between layers. Among all the possible combinations of layers involved in this interlayer interaction, the inherent variability of the physical layer in wireless systems makes this the most suitable layer for participating in such kinds of mechanisms. Indeed, system components such as medium access control (MAC) protocols, radio link control mechanisms, radio resource management schemes, and routing algorithms can benefit from some degree of awareness of the time and frequency varying characteristics of the radio channel. Seemingly the knowledge of certain information about the physical layer state allows higher protocol layers to adapt their behavior in order to improve network performance.

Apparently system performance improvements could arise from some communications between different layers, considering certain smart interactions between them in the system design. This general concept is known as cross-layer optimization [3, 4].

Figure 1 shows the OSI layered model and a subset of the possible interactions that can be considered in cross-layer design. This figure allows us to see out the vast field of research to explore in this area.

Is This New Design Structure Worth Considering?

In general, cross-layer designs and their achievable benefits are not free. Extra cost in the system is present at least in terms of additional signaling needed to extract relevant parameters from one layer that could be useful to other layers

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[5], and also in terms of the control plane information that should be exchanged and the corresponding required transmission resources occupied, and the increase in computation complexity of all the protocols involved as well. Regarding this latter topic, the realistic computational capabilities of existing hardware or its anticipated evolution should be carefully taken into account when designing cross-layer mechanisms. Indeed, computational capability can be vastly different for different types of user terminals (laptop, PDA, cell phone, etc.). Then a trade-off between overhead and efficiency improvement arises. Whether using a cross-layer approach is convenient or not in order to achieve a real net enhancement should be carefully analyzed in each study case.

In this sense, the identification and selection of relevant cross-layer parameters to be exchanged among layers will depend on the functionalities being considered for cross-layer interaction, and possibly on specific end-user application constraints and objectives. However, a generic classification can be established for cross-layer potential useful information to be exchanged between layers [6]:

1. Channel state information (CSI), including channel impulse response estimation, both in time and frequency domains, location information, terminal speed, signal strength, interference level, interference modeling, and condition number
2. QoS-related parameters, including delay, throughput, bit error rate (BER), and packet error rate (PER) measurements for each layer involved in cross-layer interaction, especially concerning the end-to-end requirements
3. Resources made available in the corresponding node, such as multi-user reception capabilities, number and type of antennas, and battery depletion level
4. Traffic pattern offered by each layer to the others, including data traffic information, knowledge of the data rate (constant or variable), data burstiness, data fragmentation, packet sizes, and information about queue sizes

Thus, another huge field of research exploration appears when considering all the possibilities for exchanging and using this control information. In each system layout, the designer should be able to select the most appropriate scheme from the available ones, and then consider the convenient use of adequate cross-layer information exchange and the proper algorithms and mechanisms in order to optimize the obtainable gain in terms that should be relevant for overall system performance.

European Research Funded Projects on Cross-Layer

Nowadays, some R&D projects funded by the European Commission deal with the study of cross-layer interactions. Two IST STREP projects, 4G MC-CDMA Multiple-Antenna System on Chip for Radio Enhancements, (4MORE, IST-507039) [7] and Jointly Optimizing Multimedia Transmission in IP-Based Wireless Networks (PHOENIX, IST-001812) [8], address cross-layer issues.

The objective of the 4MORE project is to research, develop, integrate, and validate a cost-effective low-power system on chip (SoC) solution for multi-antenna multicarrier code-division multiple access (MC-CDMA) mobile terminals, based on joint optimization of layer 1 and 2 functions. Part of the work deals with the MC-CDMA physical layer, but it is also an objective of the project to deal with baseband algorithm related activities, intended to optimize the physical and MAC layer algorithms with strong emphasis on layer 1 and 2 feedback. The aim of the PHOENIX project is to develop a scheme offering the possibility to let the application world (source coding, ciphering) and the transmission world (channel coding, modulation) talk to each other over an IPv6 proto-

col stack (network world), so they can jointly develop an end-to-end optimized wireless communication link. Despite the improvements cross-layer coupling could bring into wireless communication systems, research in cross-layer issues in those projects does not constitute the main topic.

The goals of Project E of the IST Network of Excellence on Wireless Communications (NEWCOM, IST-507325) [9] include identification of the existing gaps in European knowledge in cross-layer, and preparation of an action plan for filling them by capitalizing on project researchers' skills. The research objective of the project aims at investigating the potential benefits of cross-layer in wireless network design in relation to the methodology of separate layer design. In addition, the project intends to consider the coupling of the higher layers with the physical layer and elaborate the information to be exploited from the physical in order to optimize network performance. Furthermore, the project aims to define and implement common software platforms realizing the agreed common frameworks/models to be successively integrated and maintained.

Enhanced Radio Resource Algorithms Based on Cross-Layer Issues for 4G Networks (ERACLIN, MKTIK-2004-517518) Marie-Curie Transfer of Knowledge project objectives include the analysis of different cross-layer techniques that can be used to enhance the efficiency of wireless communication systems, and the study of the potential benefits that can be obtained from using these techniques in different environments and in particular, the explicit shift toward decentralized and adaptive MAC, radio resource management, and routing approaches. Furthermore, study of the potential benefits of incorporating channel estimation information about the future channel state in the adaptability of all the layers, and analysis of the trade-off between overheads and enhanced performance in cross-layer approaches are also among the project's objectives.

Conclusions

The main characteristic of European research in wireless networks has been focused up to now on the design and optimization of single communication layers. Significant research efforts have been made recently in order to exploit the potential benefits to be gained from interaction between layers in wireless communications systems. As a consequence, cross-layer optimization constitutes a key research topic of some European Commission funded research projects, while an integration project aims to describe the current situation in order to coordinate all research activities and fill the research gaps. A great number of industrial and academic partners are involved in these projects, and their efforts in this vast research field are growing rapidly. Furthermore, European industry and telecommunications suppliers should take into consideration cross-layer coupling and introduce it in current and future wireless communications systems.

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